

ORIGINAL ARTICLE

Development of a low-cost methodology for data acquisition and flood risk assessment in the floodplain of the river Moustiques in Haiti

Hanne Glas¹  | Philippe De Maeyer² | Sadrack Merisier³ | Greet Deruyter^{1,2}

¹Department of Civil Engineering, Ghent University, Ghent, Belgium

²Department of Geography, Ghent University, Ghent, Belgium

³ODRINO, Organisation de développement Rural Intégré du Nord-Ouest (ODRINO), Port-de-Paix, Haiti

Correspondence

Hanne Glas, Department of Civil Engineering, Ghent University, Ghent, Belgium.

Email: hanne.glas@ugent.be

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Abstract

Over the past two decades, Haiti was struck by 30 storm events and 40 floods, affecting over 3.5 million people. Being the poorest country in the Northern hemisphere, it is unable to allocate funds to risk assessment and management. Therefore, this research developed a low-cost methodology to analyse flood risk in data-sparse regions. The floodplain of the river Moustiques was chosen as study area. First, a methodology was developed and input data were gathered from existing data, literature, field data, and open source data. Then, a flood risk assessment was performed for the area. The resulting economic risk map and social risk map indicate that the region is at risk for nearly 2 million USD and has potentially 60 casualties per year. Although the assessment was performed as a quantitative analysis, the resulting maps should be interpreted qualitatively, as the values could not be validated. Nonetheless, the results clearly indicate the high-risk areas where measures should be taken. Furthermore, this research shows the potential of citizen science, in the form of a questionnaire survey conducted in the floodplain. This low-cost and fast acquisition method provided many different input data for flood risk assessment, from population data to damage factors and validation information on historic flooding.

KEYWORDS

citizen science, data-sparse regions, flooding, Haiti, risk methodology

1 | INTRODUCTION

Since its independence in 1804, the republic of Haiti is plagued by political instability, war, and revolution. Due to its turbulent history that hindered the economic and human development, there is an extremely limited availability of basic services such as water supply, sanitation, health care, and education (Kijewski-Correa, Kennedy,

Taflanidis, & Prevatt, 2018). As a result, the island state is currently the poorest country in the northern hemisphere (Rossillon, 2016). Based on the household survey of 2012, conducted by the International Household Survey Network, the World Bank concludes that over 6 million Haitians, equal to 59% of the total population, live below the national poverty line of 2.41 USD per day. Furthermore, over 2.5 million, or 24%, inhabitants fall below the

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national extreme poverty line of 1.23 USD per day. (World Bank, 2018) Moreover, year by year, Haiti is ranked lower in the Human Development Index. This index of the United Nations Development Programme (UNDP) represents the wellbeing of the population in reference to the life expectancy, the degree of education and the Gross National Income of a country. In the most recent ranking of 2017, Haiti is ranked 168th of 189 countries with a score of merely 0.498 on a scale of 0 to 1, losing 19 places in comparison to the Human Development Index of 2009 (UNDP, 2011; UNDP, 2018).

Haiti is located on the island Hispaniola, sharing its eastern border with the Dominican Republic, in the Greater Antilles archipelago of the Caribbean Sea. The islands topography is defined by high and steep mountains, as 63% of the countries surface has a slope of 20% or more (Rossilon, 2016). With a mere 3% forest cover, Haiti is one of the most deforested states worldwide (Dolisca, McDaniel, Teeter, & Jolly, 2007). Furthermore, the country is located in the Hurricane Belt, the area with the highest occurrence rate of hurricanes and tropical storms worldwide (Wallemacq, Below, & McLean, 2018). All these elements led to an extreme vulnerability towards natural hazards, in specific hydro-meteorological disasters such as storm surges and flooding.

According to the EM-DAT database, Haiti has suffered through 30 storm events and 40 floods in the past two decades, leading to a total of 7,680 deaths and more than 3.5 million people affected (CRED, 2018). In May 2004, extreme and intense precipitation, originated by a tropical depression, led to flash floods of the river Soliette, destroying 1,698 houses and damaging another 1,687. Furthermore, the flood event killed 1,059 and injured 153 Haitians (Brandimarte, Brath, Castellarin, & Di Baldassarre, 2009). Only a few months later, in September 2004, Tropical Storm Jeanne struck the country, causing widespread flooding and killing approximately 2,800 people (Colindres, Jain, Bowen, Domond, & Mintz, 2007). The island state is not only vulnerable to flood events, but also suffers regularly from seismic activity. In January 2010, a 7.0 magnitude earthquake struck the capital Port-au-Prince. This disaster caused over 220,000 deaths and displaced more than 2.3 million Haitians (OCHA, 2010). The affected area barely had time to recover, as two years later Hurricane Isaac crossed the southern peninsula of Haiti. The associated flooding affected 70,000 people, living in 180 still remaining earthquake refugee camps (Heimhuber, Hannemann, & Rieger, 2015; OCHA, 2012). On the fourth of October 2016, the passage of Category 4 Hurricane Matthew over the same peninsula caused major floods across the country, severely damaging roads and houses. The impact on the residential infrastructures was similar to the 2010 earthquake (Kijewski-Correa et al., 2018). In the

arrondissement Les Cayes, 80% of all residential buildings were destroyed (OCHA, 2016). Even more than the severity of these disaster events on their own, their high frequency and the repeated impacts on the population and infrastructure, form a major challenge for Haiti and hinder its development. This is proven by the island state's second place on the Global Long-Term Climate Risk Index ranking (Eckstein, Künzel, & Schäfer, 2018).

Hazard risk assessments attempt to minimise the impact of disasters by identifying and localising the high-risk areas and by estimating the cost of material and human losses associated with natural hazards. HAZUS-MH, for example, is a multi-hazard risk assessment tool developed by the US Federal Emergency Management Agency (FEMA) (Tate, Munoz, & Suchan, 2015). Although specifically designed for the United States, HAZUS-MH is for many researchers worldwide the standard in damage and loss estimation and thus widely used for earthquake, hurricane, and flood risk analyses (Bendito, Rozelle, & Bausch, 2014; Levi, Bausch, Katz, Rozelle, & Salamon, 2015; Park, Shin, & Cho, 2016). The available statistical and quantitative information of this tool, however, is not representative for each study area. A number of other GIS-based tools provide a more region-specific approach to flood risk mapping specifically, such as the HISS-SSM model for the Netherlands, the LATIS model for Flanders, Belgium, and the FLEMO model for Germany (Apel, Aronica, Kreibich, & Thieken, 2009; Kok, Huizinga, Vrouwenfelder, & Barendregt, 2005; Vanneuville et al., 2005). These tools all use the same methodology, that has shown adequate results in areas where extensive and detailed input data is available. In many developing countries, however, models with this methodology and high input-needs do not offer adequate results, due to the lack of detailed data. In these data-sparse regions, such as Haiti, flood risk mapping is limited to innovative approaches for specific case study areas. Brandimarte et al. (2009) developed a flood risk mitigation plan for the catchment of the river Soliette, based on a numerical model of one historic flood event. Domeneghetti et al. (2015) implemented topographical surveys and hydraulic analyses to further plan flood mitigation measures in the region. However, for most Haitian rivers, historic flood data, as well as topographic and bathymetric data, are completely inexistent. Therefore, Joseph, Gonomy, Zech, and Soares-Fraza (2018) reconstructed the riverbed and floodplain of the Cavaillon River using differential GPS and a UAV. Heimhuber et al. (2015) created a flood risk assessment for Onaville in Haiti, based on design floods derived from intensity-duration-frequency (IDF) curves in absence of historic flood information. The topography of the risk area and the river channel geometry were reconstructed using a combination of LIDAR, drone-photogrammetry and Satellite (TanDEM-X) DEMs. While these projects produced

valuable results for their respective study areas, the individuality of the different approaches and data needs hinder the implementation of these methodologies in other areas or on a wider scale. Therefore, in this research a low-cost methodology was developed for data acquisition and flood risk analysis, applicable in all data-sparse regions and on different scale levels. The generic flood risk assessment methodology developed for Annotto Bay, Jamaica, by Glas et al. (2017) was enhanced to ensure a generic approach. Furthermore, this paper focuses on the applied data acquisition methods and their possible implementation on a wider scale.

2 | FLOOD RISK METHODOLOGY

As the goal of this research was to create a generic flood risk assessment methodology, applicable to multiple areas in developing regions, this methodology needs to be clearly defined. Conventionally, risk is defined as the probability of an event and the magnitude of its consequences (Jacobs & Worthley, 1999). The United Nations, however, apply a wider definition of risk as the potential loss of life, injury or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability, and capacity (UNISDR, 2009). In this definition, capacity means the combination of all the strengths, attributes, and resources available within the system to manage and reduce disaster risks and strengthen resilience. While capacity offers a new and interesting dimension for a more complete risk assessment, this qualitative factor is difficult to

quantify economically. Therefore, a quantitative risk assessment is generally based on the conventionally used expression $\text{Risk} = \text{Hazard} \times \text{Vulnerability}$. This definition forms the base of the risk assessment methodology applied in this research (Figure 1), which focuses on two types of risk: economic and social risk (Glas et al., 2017). The former implies the potential direct damage to elements at risk, such as buildings, roads and crops, and is expressed in USD/m²/year, while the latter is calculated in number of casualties/m²/year.

The economic risk map is based on land use information, such as the location of roads, buildings, and farmlands. The associated vulnerability is calculated by combining this land use data with the replacement values per land use type, which are the costs to replace these elements at risk in case of total destruction. This calculation leads to a maximum damage map, showing the vulnerability of the region, expressed in USD/m². In a next step, the damage for one hazard event with a specific annual exceedance probability (AEP) is calculated by combining the maximum damage map with a flood hazard map that shows the flood depths. The relation between hazard and vulnerability is determined by the damage factor α , the percentage of damage for each specific element at risk for a certain flood height. The calculations for social risk follow the same workflow. However, instead of land use data, population data is required as input and combined with the flood hazard map using a mortality factor β that defines the percentage of casualties for each flood depth.

In a final step, the economic and social risk maps are created by combining the damage or vulnerability maps for the different AEPs. The created economic risk map

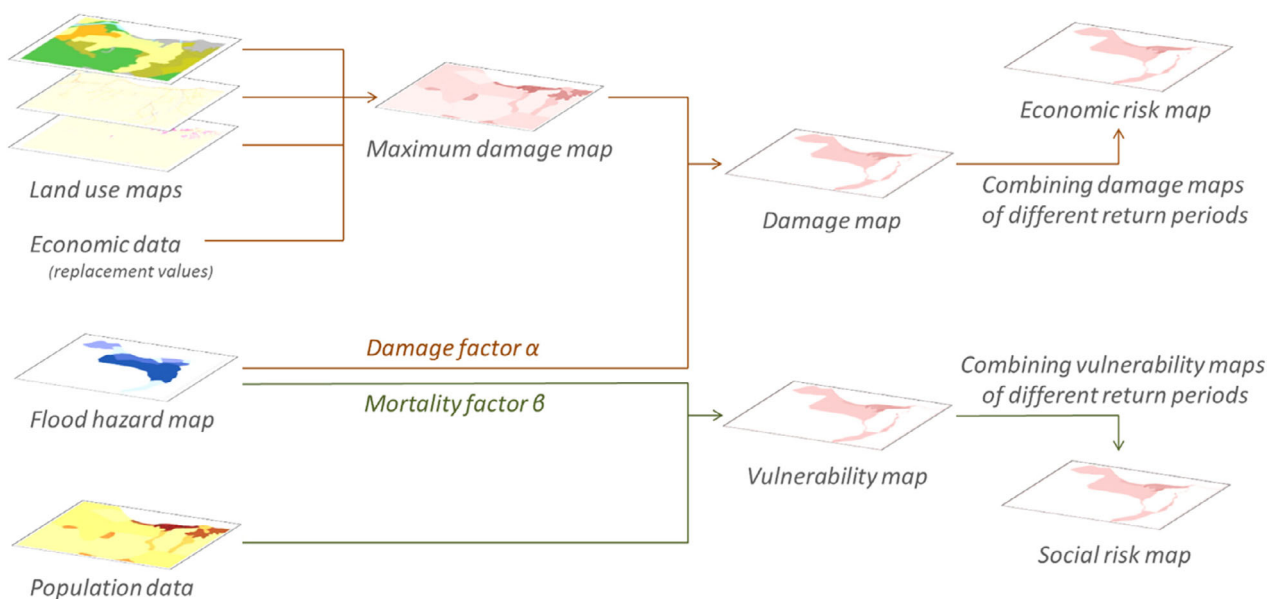


FIGURE 1 Risk assessment methodology flowchart used in the study of Annotto Bay, Jamaica (Glas et al., 2017)

shows the risk in USD/m²/year, while the social risk is visualised by the number of casualties/m²/year.

Glas, Deruyter, De Maeyer, Mandal, and James-Williamson (2016) analysed the sensitivity of this risk assessment methodology to its input data in order to define a minimum set of input data, indispensable for an adequate assessment. A main conclusion was the importance of the availability of accurate and detailed road network data. Furthermore, the possibility to use population information was proven useful for economic risk calculations in the absence of detailed building information. These findings were the base of the fieldwork and research presented here.

3 | STUDY AREA

The northwest of the island state Haiti is characterised by an overall extremely dry climate, and the 46-km-long river Moustiques is one of the rare permanent waterways in this region. Its catchment covers an area of 222 km² and has 40,000 inhabitants (Rossilon, 2016). The river rises from the mountain range Massif de Terre Neuve at a height of 697 m and flows into the sea canal Canal de la Tortue between the mainland and the island Île de la Tortue at the Baie de Moustiques.

Although the climate in the area is arid, the catchment receives a considerable amount of rain that varies between

500 and 1,200 mm per year (PROTOS, 2011). In 2010, the Haitian government distributed a nationwide flood hazard map, in which the floodplain of the Moustiques was classified as vulnerable to exceptional hazards, which are defined as cyclones, storms and hurricanes that produce as much as 600 mm precipitation in 24 hr (Government of Haiti, 2010). Several canals irrigate the agricultural lands (Figure 2) that take up the largest part of the floodplain. The drains were constructed to quickly discharge an excess of water during a flood event. For that same purpose, two tributaries of the Moustiques, called Passes in the region, were dug manually. The roads surrounding the floodplain are unpaved streets with a width of approximately 6 m, thus allowing car traffic in the region. The many smaller tracks for pedestrians are not shown on the map.

The floodplain of the river Moustiques with a total area of 20 km² and a population of 1,868 people was chosen as study area (Figure 2). Three villages are included in the study: Baie des Moustiques, located at the coastline of the bay, the neighbouring village of Nan Ti Charles, and Augustin, situated on the eastern side of the floodplain.

4 | INPUT DATA

The necessary input data can be divided into four categories, as shown in the methodology flowchart in Figure 1: land use data, economic data, flood hazard maps, and

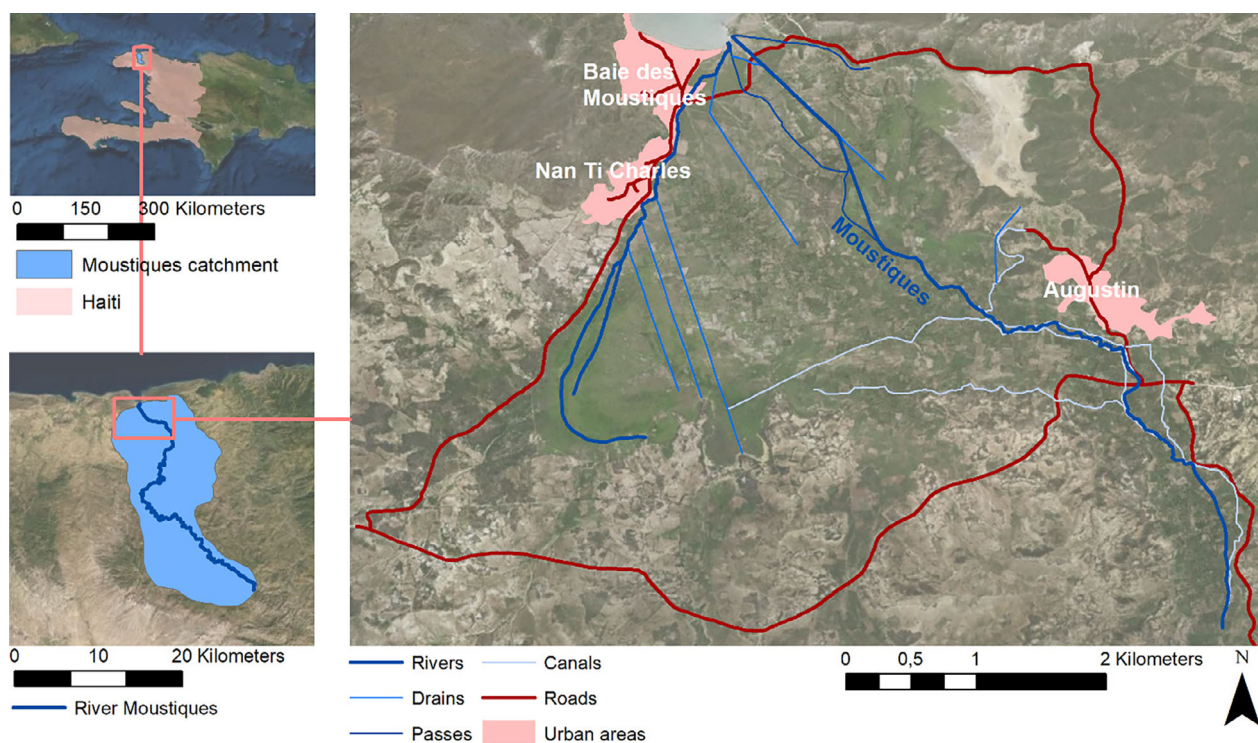


FIGURE 2 Study area: floodplain of the river Moustiques in the northwest of Haiti (based on Glas, Deruyter, and De Maeyer (2018))

TABLE 1 Overview data types and sources for the flood risk assessment of the floodplain of the river Moustiques, Haiti

Spatial data		
Data type	Acquisition source type	Exact source
Buildings	Open source data	OSM (OpenStreetMap)
Roads	New data + open source data	Field work 2018 + OSM
Crops	Existing data	Join For Water GIS data
Population density	New data	Field work 2018
Flood hazard map	New data	Antea Group
Numeric data		
Data type	Acquisition source type	Exact source
Replacement values for		
• Buildings	Literature	UCLBP (2016) + IHSI (2003)
• Roads	Literature	Collier, Kirchberger, and
• Crops	Open source data	Söderbom (2015) + MTPTC (2001) (FAOSTAT, 2017)
Damage factors for		
• Buildings	New data	Field work (2018)
• Roads	Literature	Vanneuville, De Maeyer, Maeghe, and Mostaert (2003)
• Crops	New data	Field work (2018)
Mortality factor	Literature	Vanneuville et al. (2003)

population data. The input in each of these categories can be subdivided into spatial or numeric data. While land use information, flood data, and population densities are classified as spatial data, the replacement values, and damage factors in the economic data category are numeric data. Table 1 presents an overview of the input data and their source of acquisition.

4.1 | Land use data

The land use taken into account in this research is the location of buildings, agricultural lands, and the road network. Other land use types that occur in the study area, such as wetlands and natural vegetation zones, are not included in the analysis since their economic replacement value in case of flooding is considered to be

negligible and is therefore set to 0.00 USD/m² (Vanneuville et al., 2003). The building data is a polygon shapefile downloaded from OSM.

Volunteers drew the buildings as part of a mapping action from HOT (Humanitarian OpenStreetMap Team) after the passage of Hurricane Matthew in Haiti, in October 2016. High resolution aerial imagery, donated by Digital Globe, was used as base map (HOT, 2016). For this research, the accuracy of the OSM building dataset was validated with differential GPS coordinates of a small set of buildings, acquired during fieldwork in January 2018. Furthermore, manually re-mapping all buildings in Baie des Moustiques and Nan Ti Charles, present in the Digital Globe imagery of January 2017, validated the completeness of the OSM buildings.

During the field campaign of 2018 also a large part of the road network was measured by means of differential GPS. This newly created dataset was then complemented with data from the same HOT project.

The land use type agricultural lands were extracted from an existing polygon land use dataset, acquired by the Belgian NGO Join For Water. This dataset contains three types of land use: plantain, maize, and other crops. Although the data has a high level of detail, the metadata is missing and thus, the data and method of data acquisition is unknown. Therefore, an assessment and a validation of the completeness and correctness of the crop data were done during the fieldwork GPS measurements. Figure 3 shows the land use map used for the study area, combining building, road, and crop data.

4.2 | Economic data

Each element at risk, as determined in the land use maps, is linked to a replacement value, expressed in USD/m². For all building types, the same average value was used, because Glas et al. (2016) proved in the sensitivity analysis of input data for flood risk assessments that using one average replacement value provides accurate flood risk results. The average value for buildings used for this case study is shown in Table 2 and was drafted based on two literature sources. The first was a report from the UCLBP describing the damages to civil constructions after the passage of Hurricane Matthew (UCLBP, 2016). This report describes five types of residential housing and their cost per square metres, as well as the average surface: precarious housing, *taudis* (slum housing), *ajoupas* (wooden structures), one-level housing, and apartments. Based on this information, an average replacement value per housing type was calculated. The second source is a national questionnaire survey on the living conditions in Haiti, executed by the IHSI in

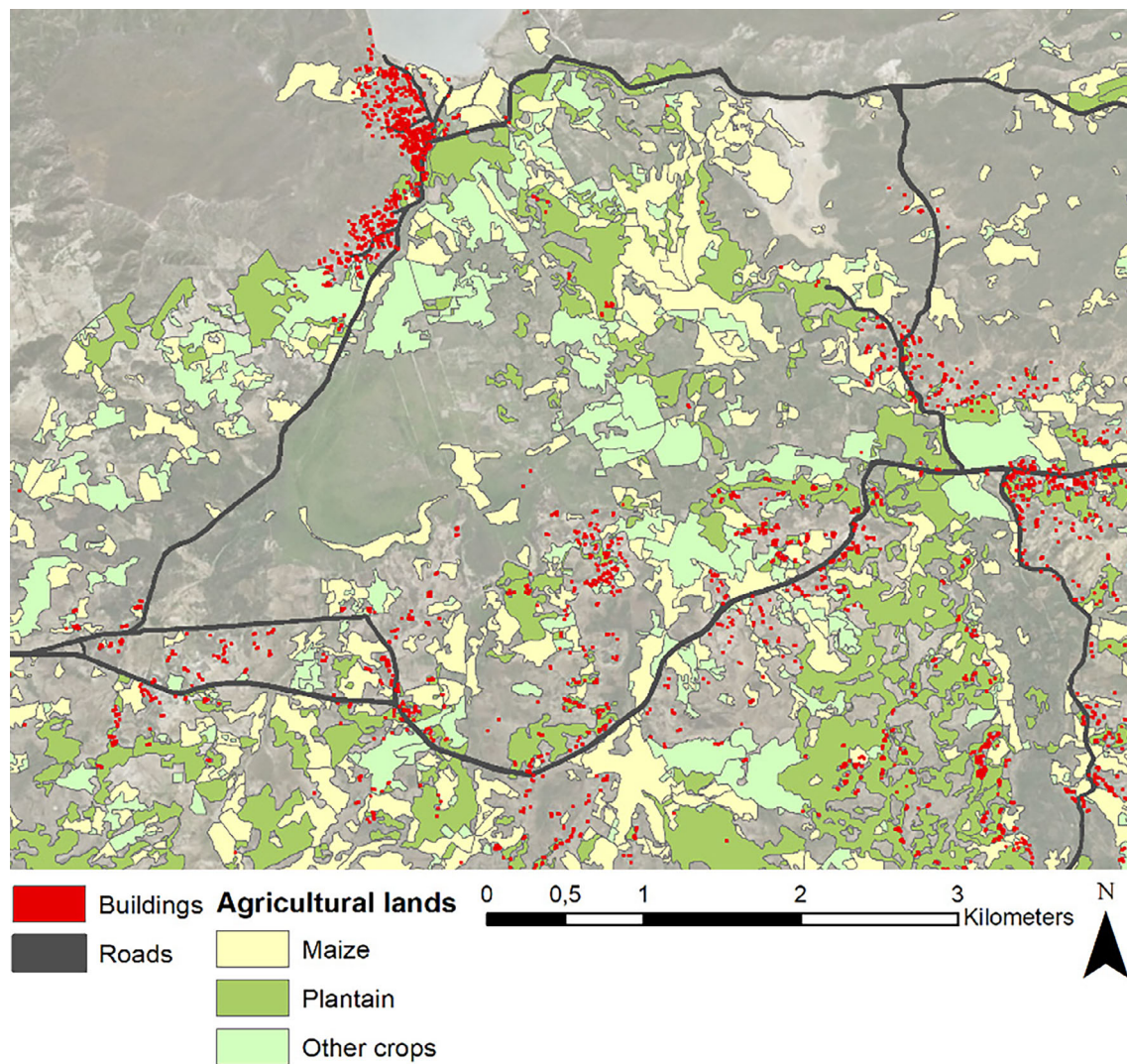


FIGURE 3 Land use map of the floodplain of the river Moustiques, Haiti (data source: OpenStreetMap, Join For Water and own data)

TABLE 2 Distribution percentages and replacement values for buildings in the catchment of the river Moustiques, Haiti, based on reports from the UCLBP (2016) and the IHSI (2003)

Housing type	Distribution percentage (%)	Replacement value (USD/m ²)
Precarious housing	34.10	10.00
<i>Taudis</i>	8.85	20.00
<i>Ajoupas</i>	8.85	65.00
One-level housing	38.80	52.00
Apartments	1.30	52.00
Other types	8.10	39.80
Average		35.01

2003 (IHSI, 2003). In the results, distribution percentages of the housing types are given for each department. The spatial building data from OSM does not differentiate in

types of housing, but the results from the questionnaires do show large differences in occurrence for each housing type. Therefore, the distribution percentages for the department Nord-Ouest were used as weights to calculate an average replacement value for a building in the study area.

All roads in the study area are unpaved roads with an average reconstruction value of 150,000 USD/km in Haiti (MTPTC, 2001). According to the ROCKS (Roads Cost Knowledge System) database, which includes eight different Haitian road projects, Haitian roads have an average width of 6 m (Collier et al., 2015). This was confirmed for the study area by random checks during the fieldwork in 2018. Combining the two literature sources, a replacement value for roads of 25.00 USD/m² was calculated. Since there is no classification in the spatial road dataset, this value was set for every road in the study area.

Finally, the replacement values for crops were calculated based on open source data from the Food and

Agriculture Organisation of the United Nations (FAOSTAT). For 15 crop types that are cultivated in the study area, the total cultivated surface and the gross production value for Haiti in 2017 were listed (Table 3). Then, the values of all crops – except for maize and plantain – were averaged to determine the replacement value. As maize and plantain are specified separately in the spatial data, these types require a separate replacement value.

TABLE 3 Replacement values for crops in the catchment of the river Moustiques, Haiti, based on data from FAOSTAT (2017)

Crop type	Replacement value (USD/m ²)
Bananas	0.14
Beans	0.04
Cassava	0.05
Coconuts	0.03
Eggplants	0.24
Fruits, fresh	0.19
Mangoes	0.46
Onions	0.11
Pumpkins	0.21
Sweet potatoes	0.04
Tomatoes	0.57
Vegetables, fresh	0.09
Yams	0.20
Average other crops	0.18
Maize	0.01
Plantains	0.14

Note: The bold values are the values taken into account in the risk assessment.

4.3 | Population data

During the fieldwork in January 2018, a survey was conducted among all 294 households residing in the three villages located in the study area, indicated in Figure 2. In the general household information section of the questionnaire, data on the composition of, and the number of people in the households, was registered (Glas et al., 2018). Each questionnaire was linked to a GPS location. For the visualisation of the number of inhabitants, this point data was aggregated in a raster with a 30 m × 30 m resolution. Then, the total population numbers were processed into a population density map (Figure 4).

4.4 | Flood hazard maps

For the whole catchment of the Moustiques, Antea Group created three flood hazard maps in raster format (30 m × 30 m) for respective AEPs of 50, 10, and 2%. Flood hazard was mapped in terms of flood heights using openLISEM, a spatial hydrological model that simulates runoff, sediment dynamics, and shallow floods (De Roo et al., 1994). Land cover input was derived from Globcover (300 m × 300 m) using a compilation of parameters based on various experimental studies as proposed by Liu and De Smedt (2004). Soil mapping units from the FAO-UNESCO Soil Map of the World were converted into likely USDA texture classes that served as base for associated hydrological parameters (Saxton & Rawls, 2006). The SRTM DEM was used as elevation input data. However, as the 30 m resolution is insufficient to describe the morphology of the river network accurately, the catchment river network was extracted as vector data from OSM and added to the model. The

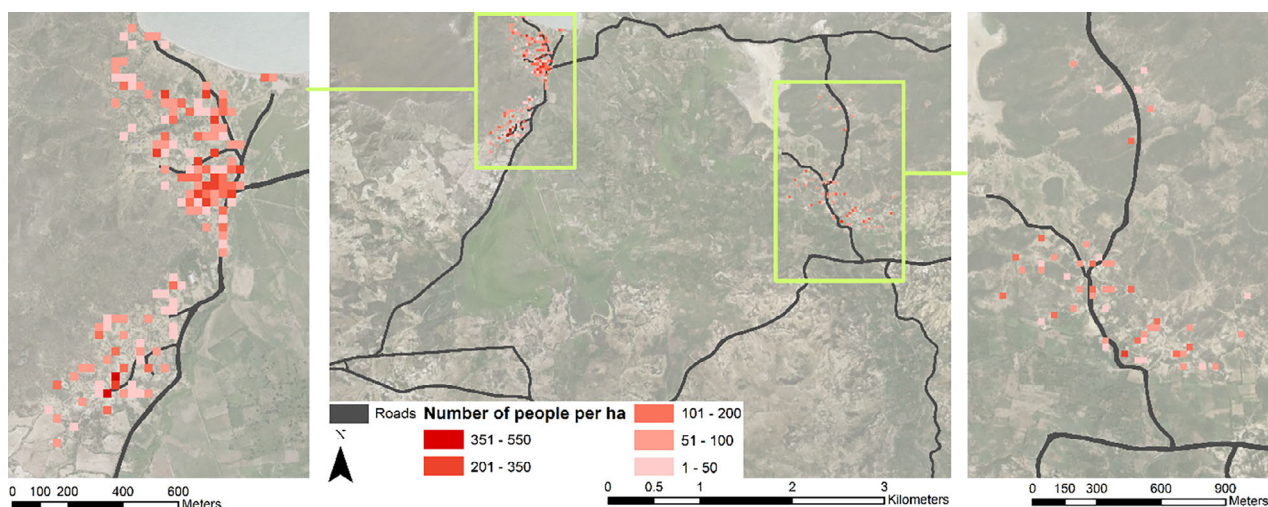


FIGURE 4 Population density map for the floodplain of the river Moustiques, Haiti

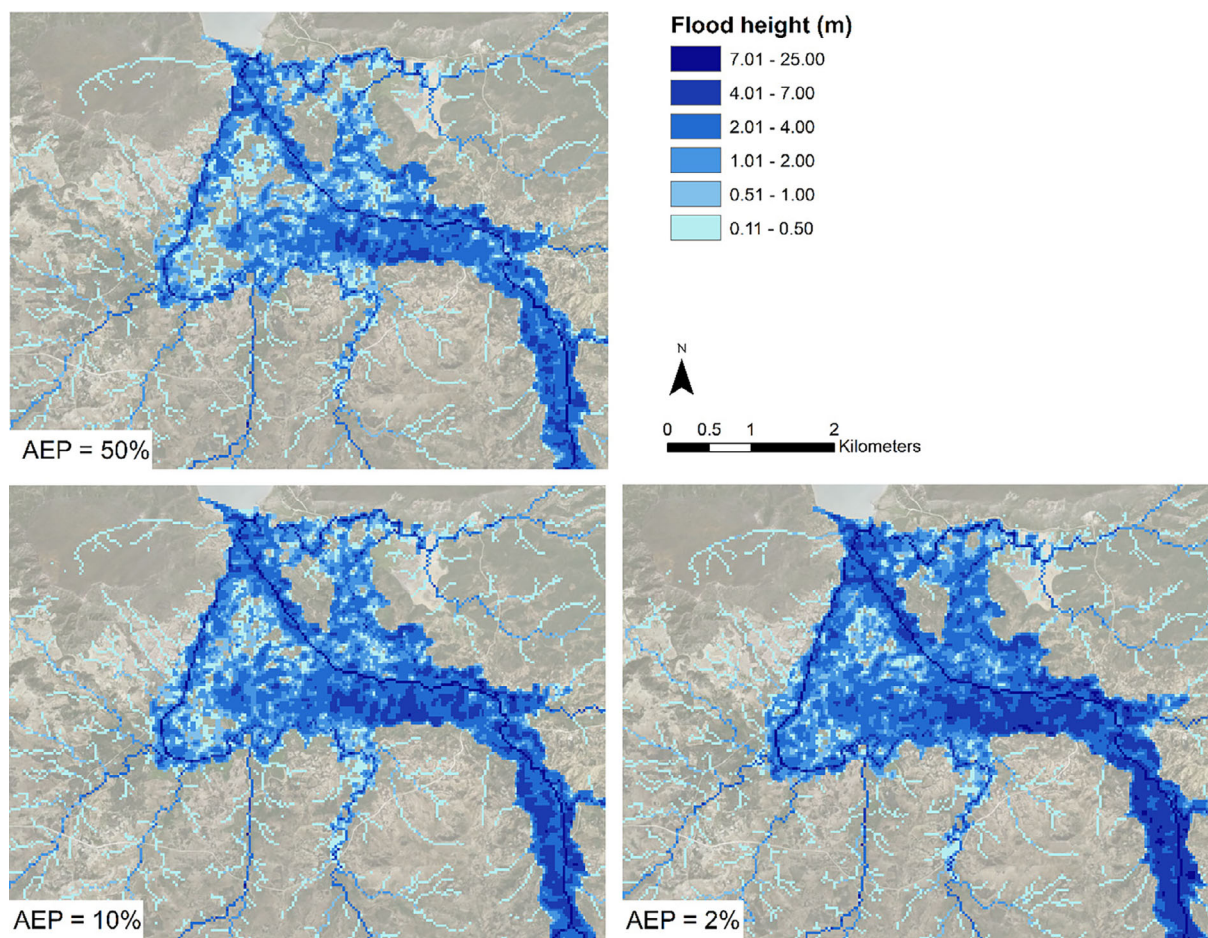


FIGURE 5 Flood hazard maps with AEP of 50% (top), AEP of 10% (bottom left), and AEP of 2% (bottom right) for the floodplain of the river Moustiques, Haiti (based on Antea Group 2018)

statistical component of flood hazard, the AEP, was incorporated based on an IDF curve for West-Puerto-Rico as there was no curve available for the study area. However, the curve was compared to Cuban and Bahamian studies and was proven consistent for the Caribbean area. The results of the flood mapping methodology in openLISEM were verified by Antea Group against a similar analysis carried out for Papua New Guinea, which was validated using existing flood hazard maps in that region (De Sutter et al., 2018). Figure 5 visualises the flood extent and water heights in the floodplain of the river for each AEP.

4.5 | Damage and mortality factors

The damage factors for the economic risk calculations were derived from different sources. For buildings, they were based on the questionnaires from 2018 in which the inhabitants were questioned about their knowledge of historic flooding and the corresponding damages to their

house ('no damage', 'limited damages', 'large damages', or 'complete destruction'). In total, 19 different flood events were described in 347 responses (Glas et al., 2018). The derived flood damage factors are visualised in Figure 6. Although these percentages do not show a linear increase, the assumption was made that a higher flood level will always result in a damage percentage equal to, or higher than, the previous factor. The in this way adapted damage factors are shown as the damage function for residential buildings in Figure 6 and were used as such as input in this risk assessment. Figure 7 visualises the functions for all land use types up to a water height of 2 m.

The damage factors for roads are based on the function that was drafted by Vanneuville et al. (2003) for roads and railroads:

$$f = \min(0.28*d; 0.18*d + 0.1; 1) \quad (1)$$

In this formula, f is the damage factor and d is the water height in metre.

FIGURE 6 Damage function for residential buildings in the floodplain the river Moustiques, Haiti. The vertical axis shows the degree of damage to the building in percentages; the horizontal axis displays the water level (Glas et al., 2018)

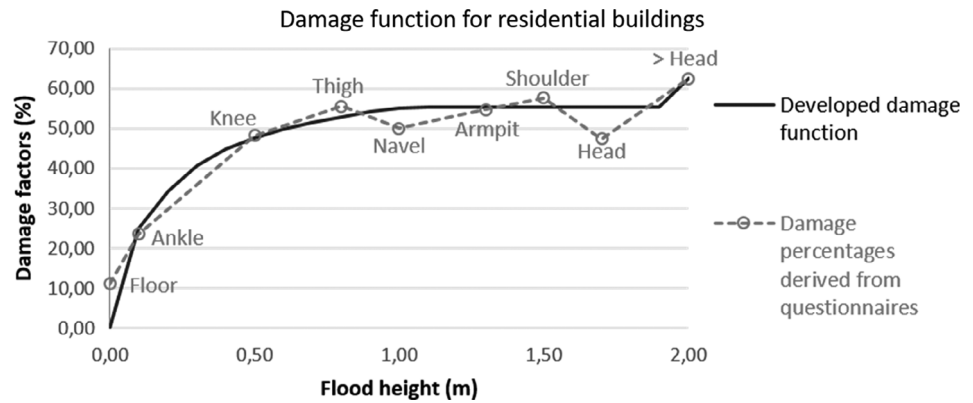
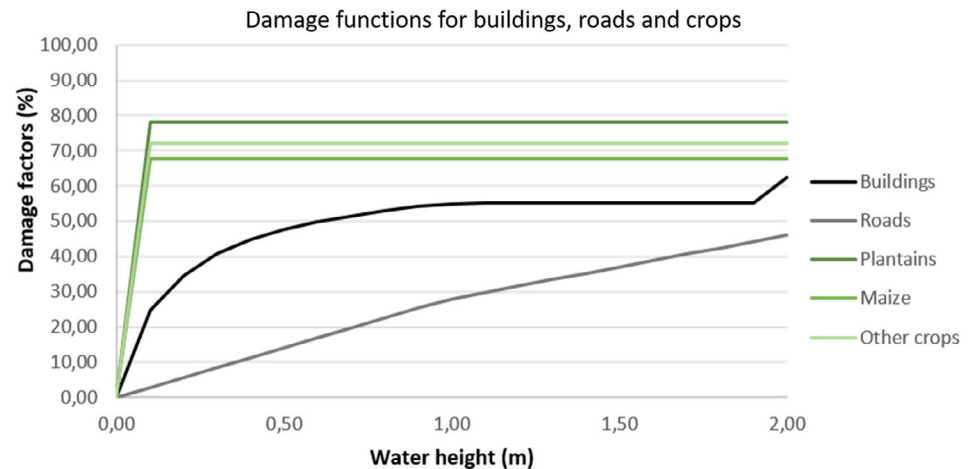


FIGURE 7 Damage functions for buildings, roads, and crops in percentages for water heights from 0.00 up to 2.00 m for the floodplain of the river Moustiques, Haiti, based on Glas et al. (2018) and Vanneuville et al. (2003)



Damage to crops is not only determined by the water height, but also by the duration of the flood and the time of the year that the flood occurs (Dutta, Herath, & Musiake, 2003). However, the flood hazard map only provides information on the water height for a certain AEP. As there are no adequate damage functions available in literature that are based on only the water height for the crops cultivated in the study area, only one damage factor is taken into account per crop type. These factors are derived from data on historic flood events gathered in the questionnaires from 2018 (Glas et al., 2018). In Figure 7, the damage functions for all elements at risk are shown separately.

To calculate the social risk, a depth-mortality function is used that defines the relation between the number of people living in an area and the flood height in that same area. The number of casualties is expressed with following depth-mortality function (Vrisou van Eck, Kok, & Vrouwenvelder, 1999):

$$N = \exp(1.16 \cdot d - 7.3) \cdot P \quad (2)$$

In this expression, N is the number of casualties, d is the water height, and P is the total population. The

mortality factor only accounts for the potential number of people killed by flooding, not for affected or wounded people.

5 | RESULTS

5.1 | Economic risk calculations

In the first step of the methodology, a maximum damage map (Figure 8) was created by combining the land use data with the replacement values for each land use type. This map visualises the damage costs for the study area if all elements would be completely destroyed.

The agricultural fields take up the largest area in the floodplain. However, due to the low replacement value, the total maximum damage for crops is less than half the damage for buildings (Table 4). The highest maximum damage value, nearly 8 million USD, belongs to the road network. In total, a value of over 13 million USD is at risk in the floodplain of the river.

By combining the maximum damage values with the water heights in the flood hazard maps using the acquired damage factors, three damage maps were

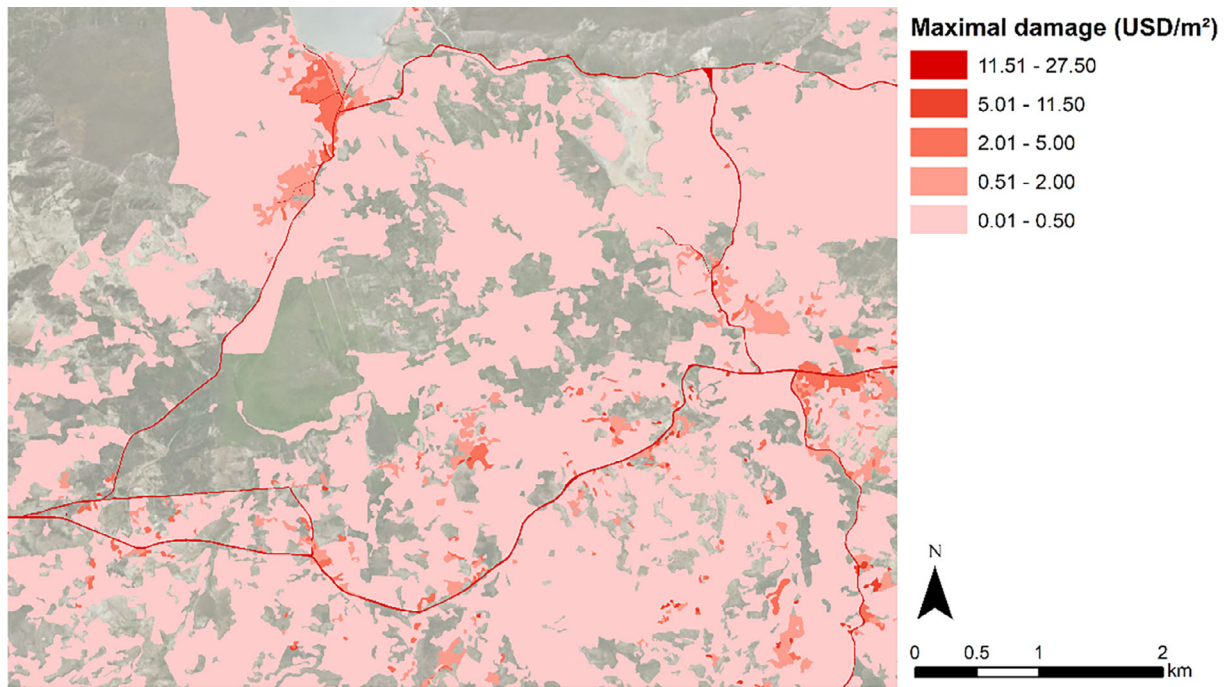


FIGURE 8 Maximum damage map for the floodplain of the river Moustiques, Haiti

TABLE 4 Overview of the maximum damage values for the floodplain of the river Moustiques, Haiti

	Total maximum damage (USD)
Buildings	3,823,250
Crops	1,598,100
Roads	7,790,900
Total	13,212,250

created with respective AEPs of 50, 10, and 2%. (Figure 9). Table 5 shows the calculated damage values for each of these three scenarios. Although visually, virtually no difference is noticeable between the damage maps, the total damage values in Table 5 show significant deviations, for example, the total damage cost of the 2% AEP flood exceeds the one of the 50% AEP flood with 15%. It is clear that the road damage cost is the determining factor for this difference.

The final step of the economic risk calculations consists of combining the three flood damage maps into one economic risk map showing the risk in USD/m²/year. This operation is defined as (Thieken, Merz, Kreibich, & Apel, 2006):

$$R = \sum_{a=1}^k AEP * D_{AEP} \quad (3)$$

In this expression, R is the risk, D_{AEP} is the damage that corresponds with the AEP, and k is the number of different flood hazard maps available. However, this expression overestimates the damage, as the same damages that occur to an element at risk in different flood scenarios are counted separately and then summed up. For example, if a house is completely destroyed by a flood with an AEP of 50%, as well as by a flood with a 10% AEP, this damage will be counted double using formula (3). Therefore, in this research, risk is expressed as a composed summation of the damages of a flood with an AEP of 100% and the extra damages of floods with lower AEPs that do not happen when a flood with a higher AEP is passing by. This is expressed mathematically with the general formula designed by Vanneuville et al. (2003):

$$R = \sum_{i=\frac{1}{AEP}}^n AEP * (D_{1/i} - D_{1/(i-1)}). \quad (4)$$

This formula implies an unlimited availability of all possible flood hazard maps, while in reality, only a limited number of flood hazard scenarios are calculated. In this study, three maps were available and formula (4) was thus interpolated accordingly. As the flood hazard map with an AEP of 100% was not created, the map with 50% AEP was used as base, resulting in:

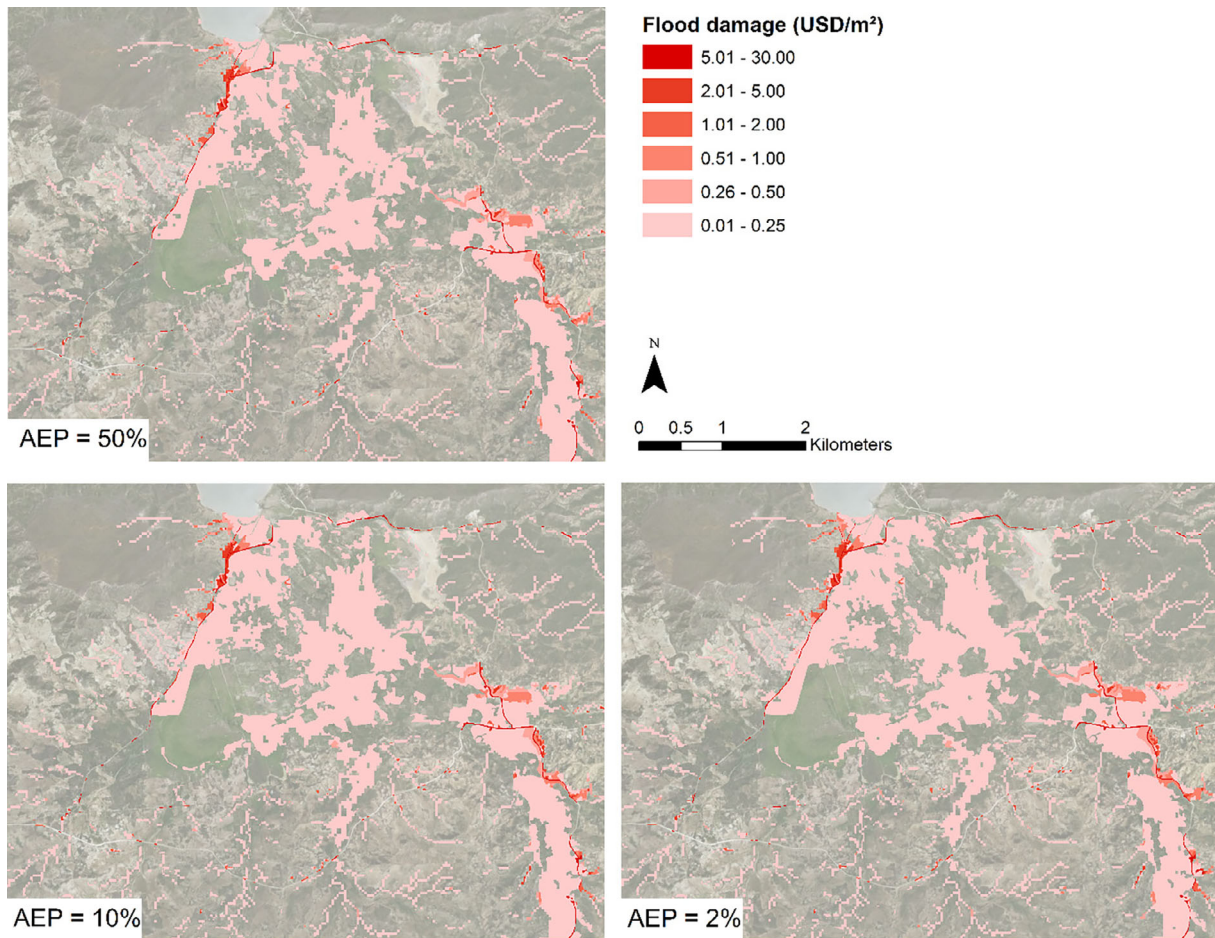


FIGURE 9 Flood damage maps for floods with AEP of 50% (top), AEP of 10% (bottom left), and AEP of 2% (bottom right) for the floodplain of the river Moustiques, Haiti

$$R = 50\% \cdot D_{50\%} + \left(\frac{\frac{1}{3} + \frac{1}{4} + \dots + \frac{1}{10}}{10 - 2} \right) (D_{10\%} - D_{50\%}) + \left(\frac{\frac{1}{11} + \frac{1}{12} + \dots + \frac{1}{50}}{50 - 10} \right) (D_{2\%} - D_{10\%}) \quad (5)$$

The result of this calculation is the economic flood risk map (Figure 10). Table 6 lists the corresponding risk values. The calculated total risk in the study area is nearly 2 million USD/year, which corresponds with 15% of the maximum damage values. The road risk takes up the largest part, 37%, followed by the building risk with 33% and the crop risk with 30%.

5.2 | Social risk calculations

For each AEP, the flood heights of the flood hazard map were combined with the population number in that same area using the corresponding mortality factor. These calculations led to a vulnerability map per AEP, showing

the potential number of casualties for each of the three scenarios. Figure 11 shows the vulnerability maps for the villages of Baie des Moustiques and Nan Ti Charles, while Figure 12 visualises the maps for Augustin.

While visually, there is little difference between the three AEP scenarios, the total number of potential casualties is 22% higher for the 10% AEP flood and even 53% higher for the 2% AEP flood in comparison to the 50% AEP flood, as listed in Table 7. The low-lying village of Baie des Moustiques has the highest potential for casualties in all three scenarios, since it is located at the mouth of the small river Ti Charles.

The vulnerability maps for the three AEPs are combined into one social risk map using the same formula (4) as in the economic risk map calculations. The result is visible in Figure 13. Table 8 lists the total number of potential casualties per village. Baie des Moustiques has the highest risk of casualties, as almost 75% of the potential casualties in the study area are inhabitants of the low-lying village.

6 | DISCUSSION

As the main reason for the lack of adequate flood risk assessment in the study area is the absence of adequate input data, this paper presents a flood risk assessment methodology based on a new, low-cost data acquisition method in the form of a questionnaire survey. As this methodology is new, it is important to evaluate and validate the outcome.

TABLE 5 Overview of the estimated damage values for a 50% annual exceedance probability (AEP) flood, a 10% AEP flood, and a 2% AEP flood for the floodplain of the river Moustiques, Haiti

	AEP = 50%	AEP = 10%	AEP = 2%
Building damage (USD)	1,282,000	1,334,000	1,390,000
Crop damage (USD)	1,176,000	1,176,000	1,176,000
Road damage (USD)	1,368,500	1,616,000	1,862,250
Total damage (USD)	3,826,500	4,126,000	4,428,250
Total damaged area (m ²)	7,047,500	7,576,750	8,052,750
Average damage (USD/m ²)	0.54	0.58	0.62
Maximum damage (USD/m ²)	27.49	27.49	27.49

The risk assessment in this research estimates that, yearly 23% of the buildings in the study area are at risk of flood damages. However, in the survey of the population of the three villages in the study area (Glas et al., 2018), 72% of the respondents indicated their home as damaged by the described flood event. The first reason for this discrepancy is that they described the most severe flood in their memory. Hence, the AEP of this flood will be most likely low. Second, homes in the department of Nord-Ouest consist on average of 2.5 buildings (IHSI, 2003). Therefore, if only one of the buildings was damaged, the entire home was indicated as damaged in the questionnaire, which leads to an overestimation.

The damage factors for buildings and crops were drafted based on the survey of Glas et al. (2018). The derived damage factors are region-specific and based on a large distribution of answers. Several other studies have proven that this form of citizen science, where data are generated purely from input from citizens, is valuable, especially in areas where other historic data is inexistent (Fast & Rinner, 2014; Hultquist & Cervone, 2018). Two hundred

TABLE 6 Overview of the total risk values for the floodplain of the river Moustiques, Haiti

	Total risk (USD/year)
Buildings	652,500
Crops	587,000
Roads	740,750
Total	1,980,250

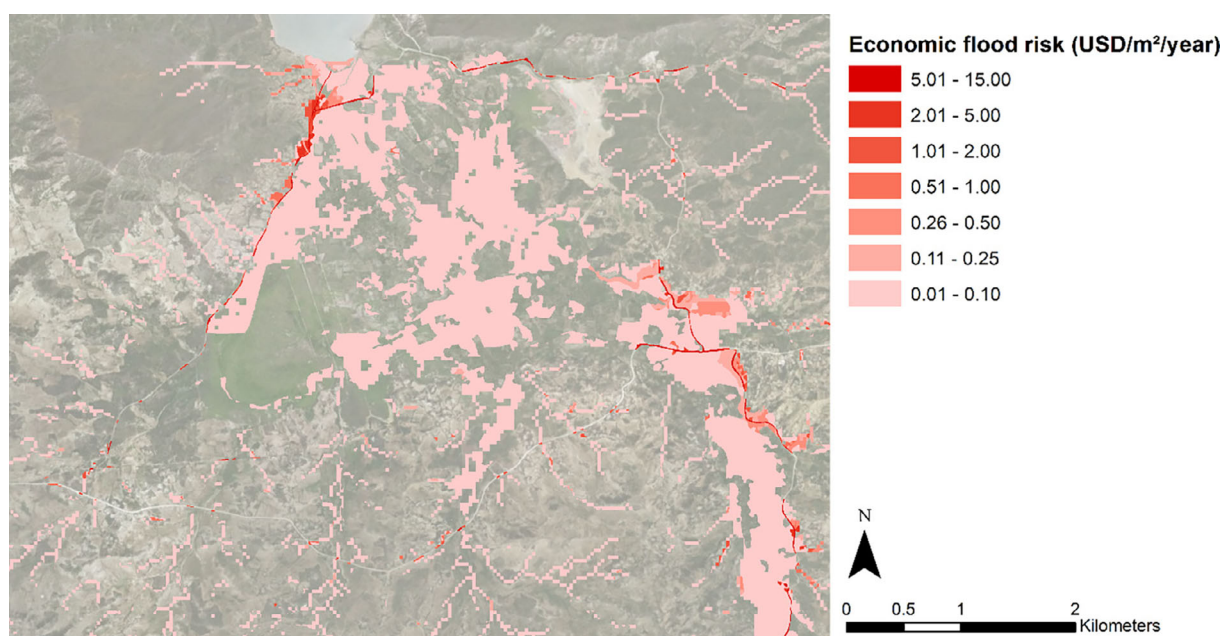


FIGURE 10 Economic flood risk map for the floodplain of the river Moustiques, Haiti

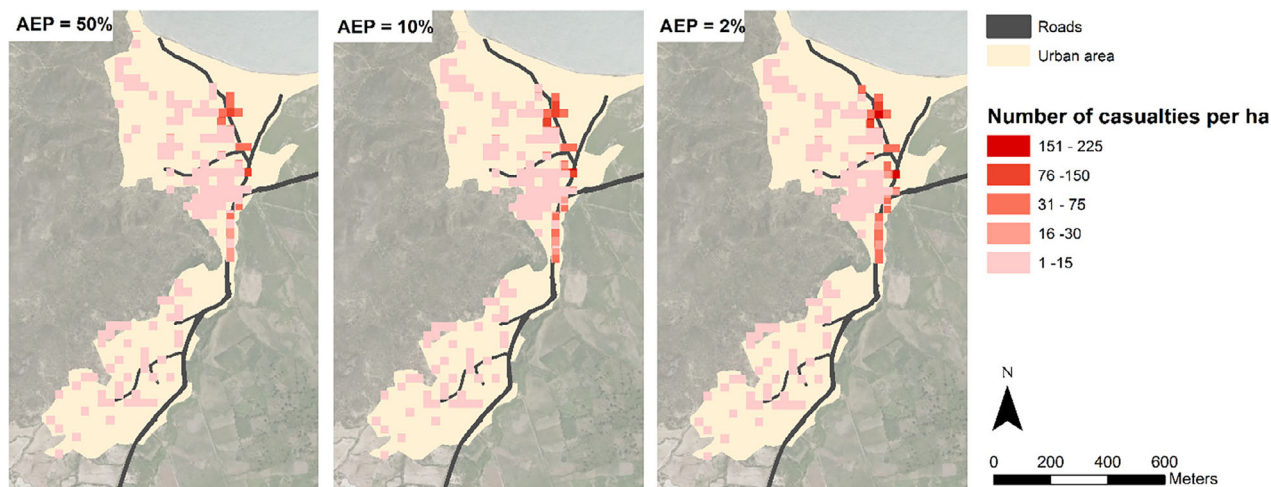


FIGURE 11 Vulnerability maps for a 50% AEP flood (left), 10% AEP flood (middle), and 2% AEP flood (right) for the villages of Baie des Moustiques and Nan Ti Charles, Haiti

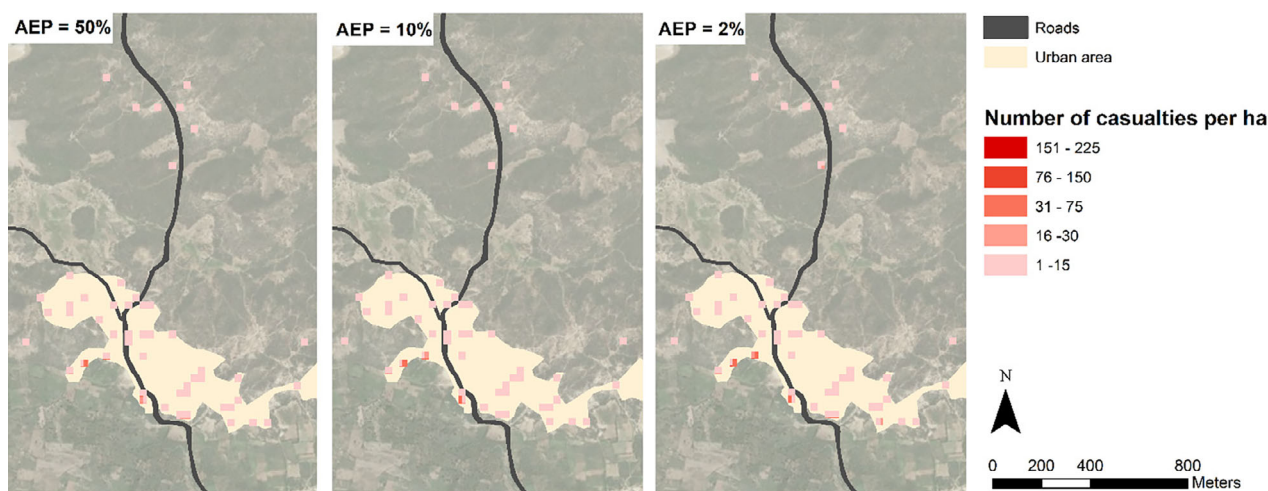


FIGURE 12 Vulnerability maps for a 50% AEP flood (left), 10% AEP flood (middle), and 2% AEP flood (right) for the village of Augustin, Haiti

TABLE 7 Overview of the potential casualties for a 50% annual exceedance probability (AEP) flood, a 10% AEP flood, and a 2% AEP flood for the villages in the floodplain of the river Moustiques, Haiti

	AEP = 50%	AEP = 10%	AEP = 2%
Baie des Moustiques	79.92	100.78	127.70
Nan Ti Charles	11.99	12.19	12.36
Augustin	17.38	20.27	26.75
Total number of casualties	109.29	133.24	166.81

and fifty of the 297 surveyed households described the flooding of January 2018 that occurred only a few days earlier. Although the answers were based on fresh

memories, which could increase the accuracy and reliability, it is important to take into account the raw emotions of people after a disaster, which may lead to spurious answers. Ideally, the surveys should have been conducted after the questioned people were recovered from the emotions.

For roads, the damage function drafted by Vanneuville et al. (2003) for Flanders, Belgium, was used. However, road construction and maintenance in Europe is difficult to compare with the Haitian context. Therefore, further research should focus on the development of a region-specific damage function for roads. The necessary input for such a function could be gathered through a questionnaire survey.

The risk assessment methodology presented in this paper is based on widely spread risk concepts and

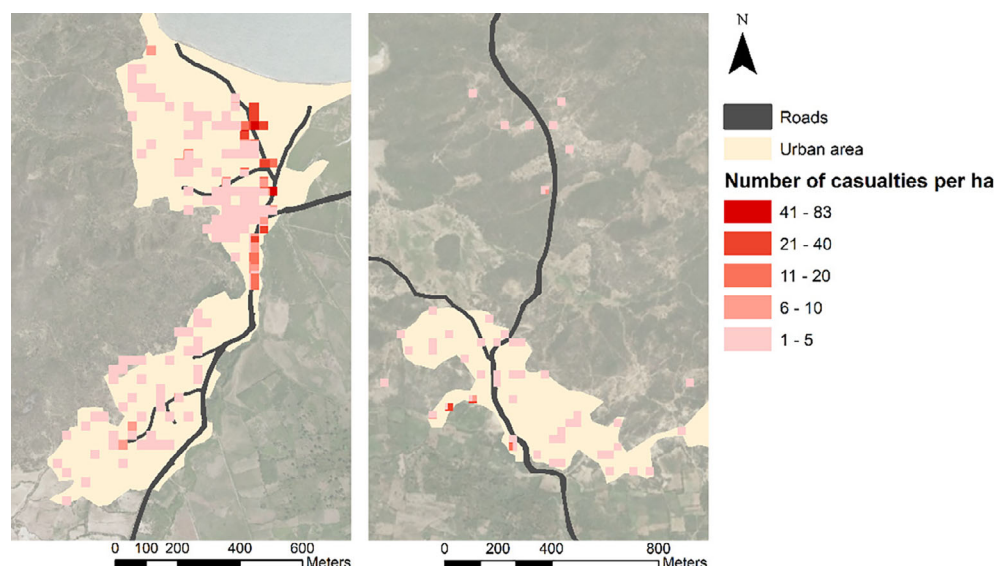


FIGURE 13 Social risk map for the villages Baie des Moustiques and Nan Ti Charles (left), and for the village Augustin (right) in the floodplain of the river Moustiques, Haiti

TABLE 8 Overview of the total number of potential casualties per year for the floodplain of the river Moustiques, Haiti

	Number of potential casualties per year
Baie des Moustiques	44.74
Nan Ti Charles	6.04
Augustin	9.46
Total	60.24

methods, described in various studies. These concepts were adapted for region-specific circumstances. While the added value of this approach lies in the applicability and suitability of the methods and results for this specific area and its inhabitants, a shortcoming of this methodology is that only direct economic damages were calculated. In other studies, indirect damages such as production losses and cleaning costs are included as a fraction of the direct damages (Grigg, Botham, Rice, Shoemaker, & Tucker, 1976; Vanneuville et al., 2005). However, calculating these indirect damages accurately is problematic, especially in data-poor regions (Penning-Rowsell et al., 2005). Therefore, indirect damage calculations were not included in the presented methodology. This, however, does not imply that these losses cannot be significant, especially in rural areas where the livelihoods of many inhabitants depend on agriculture.

In the social risk map, casualties are expressed in loss of human lives. The map visualises the number of potential deadly victims, but does not show the number of people affected by the flooding. While the total number of potential casualties is calculated at 60.24 per year or less than 4% of the total population in the area, the results of

the survey conducted by Glas et al. (2018) indicate that approximately 40% of the inhabitants are affected by a flood event. Furthermore, the overall vulnerability of the people is extremely high due to a high degree of reduced mobility: 40.26% of the population is younger than 15, 3.10% is older than 65 (Glas et al., 2018), and 11.30% of the inhabitants between the ages of 15 and 65 years old suffer from a long-term illness or are disabled. A second reason for the high number of people affected is the poor state of the limited road infrastructure, which impedes a timely evacuation. Finally, the only way of warning and informing the population in the study area before and during a flood event is through church services and word-to-mouth, in contrast to other regions in Haiti where hurricane and flood emergency warning services provide the necessary information on time.

The final step in the risk calculations is the generation of the risk maps by combining the damage maps for different AEPs. In this research, a flood map with an AEP of 100% was not available and could thus not be used as base for the risk formula. Therefore, the 50% AEP flood was used as base by multiplying the damages with the AEP. This implies that the damages that correspond with a 50% AEP flood are twice the damages of a 100% AEP flood. However, in reality, there is no linear relationship between the two flood scenarios as shown in Tables 5 and 7. Furthermore, due to the topography of the floodplain, a large flat area surrounded by steep mountains, the flood extent of a flood with a 100% AEP would not be significantly different from the extent of the 50% AEP flood, the 10% AEP flood and the 2% AEP flood. Moreover, corresponding damages would not be half of the damages of the 50% AEP flood, as is presumed in the risk formula used now. It is thus most likely that the total risk is an underestimation of the real risk, as the base of

the formula is now only half of the 50% AEP flood damages, but would be higher in reality.

7 | CONCLUSIONS

Many flood risk assessments have shown adequate and promising results in developed regions and on large scales. In many developing countries, however, the lack of detailed data has hindered the production of usable results, especially on a microscale. Therefore, this research has focused on developing a low-cost methodology for data acquisition and flood risk analysis for the floodplain of the river Moustiques in Haiti. In a first step, the risk methodology was defined, based on state-of-the-art practices as well as on the region-specific conditions and restrictions. Then, the necessary input data was listed and a low-cost data acquisition methodology was presented to gather the missing information.

Conducting a survey of the population by questionnaires is a fast and targeted acquisition method. Furthermore, it provides region-specific data, allowing an assessment on microscale. Questionnaires can provide information on historic floods that is otherwise inexistent. Finally, this information can be gathered at any time, eliminating the need to perform measurements at the time of a disaster. This is a big advantage, as this study area, as many others, is often inaccessible during a flood. However, the method has a few important disadvantages that require care and caution in the processing. Extreme events such as flooding can have a traumatic effect on people, causing their memory of the event to be unreliable. Furthermore, the composition of the questions is extremely important as unclear questions can cause confusion and unusable answers. While some of these concerns can be addressed, for example by briefing the pollsters and providing background information, there is still a risk of systematic bias. This form of citizen science is a great added value in flood risk assessment in data-sparse areas, but needs more research and validation based on other, more objective, data sources. Another data source that needs further research is satellite imagery, for example the radar satellite from Sentinel 1 that can provide observations through cloud cover and, as open source data, can provide objective region-specific input for flood risk analysis.

Every flood risk assessment is based on certain assumptions, generalisations, and aggregated data in order to evaluate the risk and potential damages of future flooding. Therefore, it is always difficult to validate the results of the assessment and evaluate the accuracy of the methodology. In this research, as well as in other data-sparse study areas, this validation procedure is extra

complicated due to inexistent historic flood data. While the results could not be validated, the input data and methodology could. Based on the results of the sensitivity analysis performed by Glas et al. (2016), the determining input data was gathered and the accuracy and completeness of this data were tested and validated. While the quantitative results are too uncertain to be used as a decision factor, a qualitative approach of the risk map, that shows the high-risk areas and indicates where measures should be taken, does provide decision makers with an adequate tool to allocate the available funds. The locations of these high-risk areas are confirmed by the results of the questionnaire survey.

The floodplain of the river Moustiques is a rural area where agricultural lands take up the lion's share of the land use. The potential risk to these crops per square metres is only a fraction of the potential risk to buildings and roads. This leads to a risk map where the high-risk areas are concentrated around the built-up areas. The difference in risk between the different crops is invisible in such a map, as all agricultural lands are indicated as low-risk, compared to the buildings and roads. Furthermore, the methodology only takes into account direct losses, while many of the households in the study area depend on the crop harvest for their livelihood. Crop damages will thus have a large indirect impact on the community. Therefore, future research should explore incorporating indirect losses in the risk methodology. Moreover, other visualisation methods could allow a better interpretation of the risks per land use type. Urban zones need other mitigation and adaptation measures than rural zones. By providing the risk information on direct and indirect damages per land use type, decision makers will be better equipped to allocate the correct measures to the correct zones.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Hanne Glas  <https://orcid.org/0000-0003-1274-7139>

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